



Systematic Review

Spontaneous Interpersonal Synchronization of Gait: A Systematic Review



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KEYWORDS

Gait;
Locomotion;
Motor activity;
Rehabilitation

Abstract Objective: To systematically review the existing evidence of spontaneous synchronization in human gait.

Data Sources: EBSCO, PubMed, Google Scholar, and PsycINFO were searched from inception to July 2020 using all possible combinations of (1) “spontaneous interpersonal synchronization” or “spontaneous interpersonal coordination” or “unintentional interpersonal synchronization” or “unintentional interpersonal coordination” and (2) “human movement” or “movement” or “walking” or “ambulation” or “gait.”

Study Selection: Studies had to focus on spontaneous synchronization in human gait, be published in a peer-reviewed journal, present original data (no review articles were included), and be written in English. The search yielded 137 results, and the inclusion criteria were met by 16 studies.

Data Extraction: Participant demographics, study purpose, setup, procedure, biomechanical measurement, coordination analytical technique, and findings were extracted. Our synthesis focused on the context in which this phenomenon has been studied, the role of sensory information in the emergence of spontaneous interpersonal synchronization in human gait, and the metrics used to quantify this behavior.

Data Synthesis: The included 16 articles ranged from 2007-2019 and used healthy, primarily young subjects to investigate the role of spontaneous interpersonal synchronization on gait behavior, with the majority using a side-by-side walking/running paradigm. All articles reported data supporting spontaneous interpersonal synchronization, with the strength of the synchronization depending on the sensory information available to the participants.

Conclusions: Walking alongside an intact locomotor system may provide an effective and biologically variable attractor signal for rehabilitation of gait behavior. Future research should focus on the utility of spontaneous interpersonal synchronization in clinical populations as a noninvasive method to enhance gait rehabilitation.

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List of abbreviations: SMS, sensorimotor synchronization.

Disclosures: none.

Presented to the North American Society for the Psychology of Sport and Physical Activity (June 11-12, 2020), and the presentation abstract was published in the conference’s official journal (Felsberg D, Rhea C. *J Sport Exerc Psychol Suppl* 2020;42:535). A copy of the conference abstract publication has been included in our submission.

Cite this article as: *Arch Rehabil Res Clin Transl.* 2021;3:100097.

<https://doi.org/10.1016/j.arrct.2020.100097>

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Sensorimotor synchronization (SMS) refers to the coordination of human movement with a rhythmic external stimulus,¹⁻³ which has long history of being used for clinical assessment and rehabilitation.⁴⁻¹⁰ This includes research on populations with cerebral palsy,¹¹ stroke,¹² multiple sclerosis,¹³ Parkinson disease,^{14,15} traumatic brain injury and spinal cord injury,¹⁶ and older adults.¹⁷ The rhythmic stimuli can range from metronomes to music to social interactions. The current framework for SMS includes both intentional and unintentional synchronization. With intentional synchronization conditions, individuals are explicitly instructed to synchronize with a given cue. Conversely, unintentional conditions involve the spontaneous synchronization between an individual and a rhythmic stimulus.

Intentional synchronization has been widely investigated as a rehabilitation tool to improve motor control specifically in the context of gait.¹⁸⁻²² For example, in patients with Parkinson disease, gait variability was decreased with intentional synchronization of stepping to an auditory cue.^{22,23} Similarly, side-by-side stepping has been proposed as a gait rehabilitation intervention.²⁴ This type of interpersonal synchronization may stimulate areas of the brain that are active during movement imitation, which could aid in development of motor skills.²⁵ However, less is known about the effects of *spontaneous* (ie, unintentional) interpersonal synchronization on the gait dynamics and its implications for use as a rehabilitation intervention to improve motor outcomes. This is despite the fact that much has been learned in recent decades about spontaneous synchronization in physical and biological systems,^{26,27} with the original observation dating back more than 3 centuries ago.²⁸

When people interact socially, they tend to spontaneously coordinate their movement patterns.²⁹ For example, when walking together 2 individuals may naturally, and unintentionally, synchronize their stepping.³⁰ Unintentional interpersonal synchronization has been demonstrated even under conditions where participants were explicitly instructed not to synchronize.³¹ From a motor learning perspective, the spontaneous interpersonal synchronization may provide a more passive control of movement, thereby improving overall function and automaticity of the skill.³² Moreover, spontaneous synchronization between individuals during a walking task may produce less task constraints compared with intentional interpersonal synchronization, making it a potentially valuable rehabilitation tool.^{32,33} However, the context in which this phenomenon has been studied has yet to be systematically investigated.

Intertwined with the tasks used to study this phenomenon in gait is the role of sensory information. That is, what is the information medium that allows spontaneous synchronization in gait to naturally emerge? In physics, 2 or more systems can couple around a shared dynamic, even if their starting or natural dynamics differ. This can be visualized in the classic example of multiple metronomes starting at slightly different times. If on a solid surface where very little information (ie, vibration in this example) is shared between the metronomes, they will continue to “ticktock” at their initial and individualized frequency and cycle. However, if they are placed on a board sitting on top of 2 soda cans, the vibration of each metronome influences the others, such that they will eventually lock into a common frequency and cycle, and ticktock at the same time. A mathematical model

for this phenomenon was put forth by Pantaleone.³⁴ While this is an example from physical sciences, the idea of spontaneous synchronization is prevalent in biological sciences as well,^{26,27} with the origin of the phenomenon dating back to the 1600s.²⁸ A systematic examination of the sensory information that leads to the strongest spontaneous synchronization in human gait has not yet been completed.

Lastly, the metrics used to quantify such a spontaneous synchronization between 2 humans in gait have not been critically appraised. While metrics have been identified that quantify synchronization in human motor tasks,^{3,35} the manner in which these metrics have been applied to study spontaneous interpersonal synchronization in human gait has not been identified. Thus, the purpose of this review was to systematically survey the current state of the literature investigating spontaneous interpersonal synchronization in human gait with respect to the types of tasks used to study this phenomenon, the sensory information used to test the strength of the synchronization, and the types of metrics used to index spontaneous interpersonal synchronization.

Methods

Data sources and searches

The systematic review protocol guidelines described by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis were adopted and applied to this review.³⁶ Keyword searches were performed using database searches of EBSCO, PubMed, Google Scholar, and PsycINFO with no year restrictions. The search parameters used included all possible combinations of (1) “spontaneous interpersonal synchronization” or “spontaneous interpersonal coordination” or “unintentional interpersonal synchronization” or “unintentional interpersonal coordination” and (2) “human movement” or “movement” or “walking” or “ambulation” or “gait.” The specific search algorithm is provided in [fig 1](#). Keyword searches were performed in July 2020. To ensure completeness, gray literature—defined as articles that were not returned from the search algorithm but found through other sources—was included. Gray literature for this systematic review was found by examining the reference lists of the articles that were originally returned from the search algorithm. All articles were screened based on the specific inclusion and exclusion criteria outlined in the Study selection section.

Study selection

Both authors independently performed the steps below. First, duplicates were removed from the article list returned from the search. Next, the remaining articles were screened for inclusion criteria by examining the title and abstract. Articles were excluded if they (1) were not written in English; (2) were a nonresearch text (ie, book chapter); (3) were a review article; (4) were a thesis, dissertation, or conference abstract; or (5) did not focus on human movement synchronization. Full texts of the remaining articles were accessed, and articles were further excluded if they did not focus specifically on spontaneous interpersonal synchronization in human gait. The remaining

Database	Search Algorithm
EBSCO, PubMed, Google Scholar, and PsycINFO	(spontaneous interpersonal synchronization or spontaneous interpersonal coordination) OR (unintentional interpersonal synchronization or unintentional interpersonal coordination) AND (human movement or movement or walking or ambulation or gait)

Fig 1 Database search algorithm.

articles represented the list of included articles for this review. The authors compared their lists and resolved any differences prior to the qualitative synthesis.

Results

Study selection

The initial searches of EBSCO, PubMed, Google Scholar, and PsycINFO yielded 130 articles, with an additional 7 identified via other sources. The complete article selection process is illustrated in [fig 2](#). Of the 137 initially included articles, 37 were duplicates. After removal of duplicates, 100 were screened through titles and abstracts. Through the screening process, 50 were excluded because they were nonresearch text, systematic review, or did not investigate synchronization of human movement. Of the 50 remaining articles, 34 were excluded because they did not investigate the role of spontaneous interpersonal synchronization of gait in humans. Thus, the remaining 16 articles^{24,30,33,37-49} were selected for inclusion, which ranged in years from 2007-2019.

Synthesized findings

A summary of each study's demographics and purpose of each can be found in [table 1](#). Overall, all articles

demonstrated fluctuations in gait dynamics favorable for spontaneous interpersonal synchronization.

Participants and locomotion task characteristics

All 16 articles used healthy, primarily young subjects to investigate the role of spontaneous interpersonal synchronization on gait behavior. Fifteen articles used a side-by-side walking/running paradigm, with 9 using treadmill walking and 6 using overground walking or running. One article used an inline walking paradigm that consisted of 2 people in a single file line walking closely to each other. A summary of task procedures and findings can be found in [table 2](#).

Role of sensory information

The degree of spontaneous interpersonal synchronization was affected by the sensory information provided (or manipulated) in each study. In all studies, visual information between the participants was available all or some of the time, the medium by which spontaneous interpersonal synchronization has been most extensively studied. Seven studies explored the role of tactile information directly relative to their partner in addition to or in absence of visual information,^{38-40,44,47-49} with 5 of those studies using hand-holding as the manipulation to provide interpersonal tactile sensory information.^{38,44,47-49} Four of the

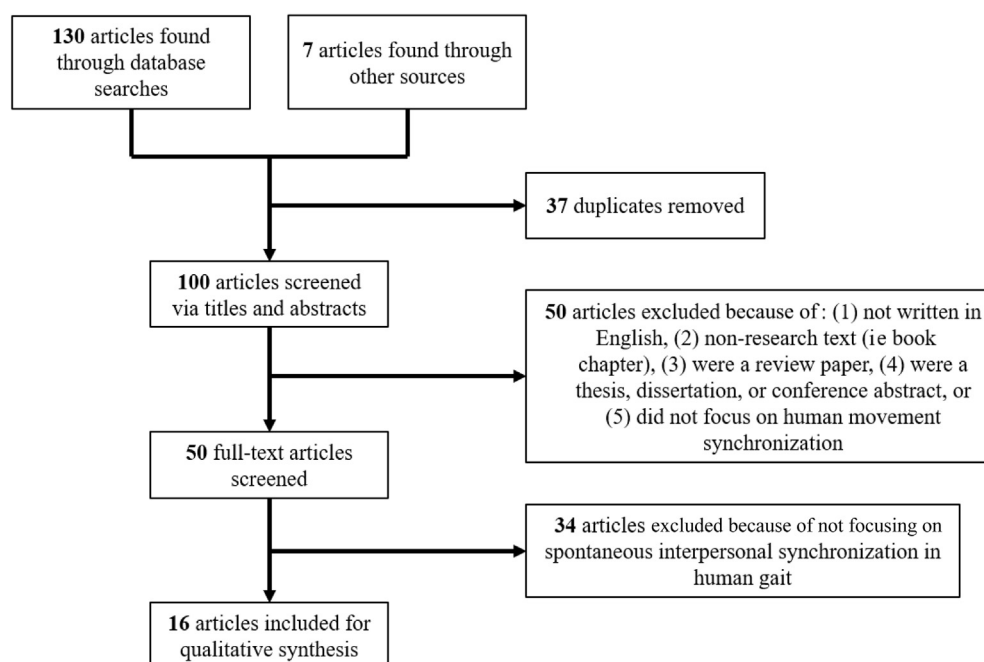


Fig 2 Flowchart of systematic article search and inclusion for review.

Table 1 Summary of the demographics of included articles investigating spontaneous interpersonal synchronization in gait

Authors	N	Population	Mean Age (y)	Purpose
Blikslager and de Poel ³⁷	2	Professional sprinters	Not reported	Role of spontaneous interpersonal synchronization in the modification of athletic performance
Chambers et al ³⁸	348	City walkers	Estimated to be 30.6	Apply pose estimation to online videos to ask how people synchronize their movements when they walk side by side under naturalistic conditions
Harrison and Richardson ³⁹	12	Healthy young adults	19.9	Role of visual and mechanical coupling on spontaneous interpersonal synchronization of leg movements to produce gaits associated with quadrupedal locomotion
Nessler et al ²⁴	14	Healthy young adults	23.3	Investigate kinematic variability using nonlinear and traditional gait analysis during treadmill walking with various levels of side-by-side synchronization
Nessler and Gilliland ⁴⁰	40	Healthy young adults	24.4	To quantify the relationship between leg length, select sensory feedback variables, and spontaneous interpersonal synchronization of gait
Nessler and Gilliland ³³	12	Healthy young adults	24.7	Investigate normal treadmill walking with treadmill walking under intentional and spontaneous interpersonal synchronization conditions
Nessler et al ⁴¹	48	Healthy young adults	22.7	Investigate prediction that spontaneous synchronization might be influenced by interpersonal changes in gait mechanics
Nessler et al ⁴²	26	Healthy young adults	23.8	To compare the effects of paired walking under conditions where (1) subconscious synchronization was likely to occur because walking patterns were similar between partners and (2) synchronization was not likely to occur because walking patterns differed substantially between partners
Nessler et al ⁴³	50	Healthy young adults	24.5	Investigate the interaction between interlimb coordination and unintentional interpersonal synchronization of gait in healthy individuals in response to unilateral ankle loading
Sylos-Labini et al ⁴⁴	16	Healthy adults	38	Role of physical interaction in spontaneous interpersonal synchronization
van Ulzen et al ³⁰	22	Healthy young adults	Not reported	Investigate how individuals synchronize their lower extremity movement while walking side by side
van Ulzen et al ⁴⁵	12	Healthy young adults	Not reported	Investigate if the Haken-Kelso-Bunz model applies to rhythmic interlimb coordination in side-by-side treadmill walking
Varlet and Richardson ⁴⁶	2	Professional sprinters	Not reported	Role of spontaneous interpersonal synchronization in the modification of athletic performance
Zivotofsky and Hausdorff ⁴⁹	28	Healthy adolescents	13.8	Role of sensory feedback mechanisms in spontaneously interpersonal synchronization of gait
Zivotofsky et al ⁴⁸	28	Healthy young adults	26	Investigate the sensory mechanisms underlying spontaneous interpersonal coordination in overground walking
Zivotofsky et al ⁴⁷	32	Healthy young adults	26	Role of attention spontaneous interpersonal synchronization of gait in overground walking

hand-holding studies demonstrated increased spontaneous interpersonal synchronization when tactile feedback was available (only Chambers et al³⁸ did not). The remaining 2 studies that explored the role of direct interpersonal tactile information used a mechanical connection between the 2 participants, with both studies showing increased synchronization relative to other sensory information.^{39,40} Two studies manipulated tactile information but only relevant to a single participant. This was executed by Nessler et al

by having 1 participant walk at an increased or decreased treadmill slope relative to their partner (which affected synchronization)⁴¹ and using unilateral ankle loading (which did not affect synchronization).⁴³ Lastly, spontaneous synchronization was found to be higher in pairs with lower leg length discrepancy.⁴⁰ That is, people who had more similar leg lengths exhibited stronger spontaneous synchronization, which may be an important observation for clinical practice.

The findings regarding the role of other types of sensory information in spontaneous synchronization was mixed. Visual and tactile information were found to lead to the strongest spontaneous interpersonal synchrony in one study,³⁹ tactile information was shown to be superior in another study, and tactile and auditory information were shown to be superior in yet another study.⁴⁸ In some studies, gait pacing was prescribed for the first part of the trial and then turned off to see if the participants spontaneously synchronized. The study by van Ulzen et al used an auditory metronome in this context while visual information about their partner was available.⁴⁵ Conversely, Sylos-Labini et al used a similar design, except they removed visual information about their partner, and tactile information was available in some experimental conditions.⁴⁴

Methods used to quantify synchronization

The strength of spontaneous synchronization between paired walkers was quantified in various ways across studies. A summary of the measurements and analyses used to analyze spontaneous interpersonal synchronization and other aspects of gait can be found in [table 3](#). The most prominent methods were relative phase (12 of 16 studies)^{30,37-40,42-48} and frequency/phase locking (12 of 16 studies).^{24,30,33,39-44,46-48} Phase shift was used in 3 studies,^{45,47,48} and Gait Synchronization Index—the ratio between the observed and maximum strength of synchronization—was used in 2 studies.^{47,48} The following analyses were used in 1 study: cross-spectral coherence,⁴³ an objective synchrony score (scale -3 to 3),⁴⁹ gait asymmetry,⁴³ and phase coordination index⁴³—a measurement of interlimb coordination between the left and right legs. To identify changes at the individual participant level (ie, nonsynchronous activity), linear metrics such as mean step length, stride time, or joint/segment angles were used in 4 studies,^{24,33,41-44,47,48} along with the nonlinear metrics of Lyapunov exponent^{24,42} and approximate entropy.⁴²

Discussion

SMS is a growing research area that can be separated into 2 lines of inquiry: (1) intentional synchronization or (2) unintentional (spontaneous) synchronization. The former has been widely investigated as gait rehabilitation tool.^{19,22,23,50,51} However, despite the fact that spontaneous synchronization is a well-studied phenomenon in physics and natural systems,²⁶ less is known about spontaneous interpersonal synchronization, especially the context of human gait. Highlighting common themes in this emerging line of research could help to not only understand basic principles of coordinated human movement but may also have clinical rehabilitation application, such as developing best practices for a physical therapist to use side-by-side walking as a therapeutic modality with a patient to alter dysfunctional gait dynamics.

Through this review, it is evident that the study of spontaneous interpersonal synchronization is in its infancy. From the 137 articles retrieved, only 16 were found to have studied spontaneous interpersonal synchronization in human gait. Thus, our synthesis of these articles was somewhat limited because of the paucity of research in this area.

Nevertheless, some themes emerged that may help guide future research in this area.

The first question of interest was the context in which this phenomenon has been studied. Nearly all articles included in this review used a side-by-side walking or running paradigm. This was not surprising because there are numerous examples in natural environments in which side-by-side walking elicits spontaneous synchronization (see [fig 1](#) in Zivotofsky and Hausdorff⁴⁹ for 2 such examples). This observation was the motivation behind the work by Chambers et al, who used public YouTube videos of 2 people walking in city environments and an innovative data extraction method to quantify this often seen observation.³⁸ Only Harrison and Richardson used an inline walking protocol.³⁹ This protocol has been used to study how pedestrians use visual information to follow each other in the context of crowd dynamics,⁵² but to our knowledge, Harrison and Richardson are the only researchers to use it in the context of spontaneous interpersonal synchronization.

Our second question focused on sensory information that was available (or manipulated) during the studies. In human gait, spontaneous interpersonal synchronization is thought to occur primarily through the information medium of 1 or more of our sensory systems: visual, auditory, and/or tactile information. Our review revealed that all included articles incorporated visual information in all or part of their study design. In some cases, visual information was purposely taken away as a means to determine the extent to which spontaneous interpersonal synchronization relies on vision,^{39,40,47,48} whereas others manipulated auditory information^{44,45,48,49} or tactile information.^{38-40,44,47-49} The general finding (although not a consensus) is that when tactile information is available, it leads to stronger synchronization relative to visual or auditory information. This speaks to the salience of shared information between 2 people because a physical connection appears to have a stronger influence on the shared coordination dynamics relative to visual or auditory information. This may be because of attention factors (ie, it is hard to not attend to someone pulling on your hand but perhaps easier to not attend to information in your visual periphery) or perceptual thresholds related to each sensory system, but these postulates should be empirically tested in future research.

Our third inquiry was the manner in which synchronization has been quantified in the included studies. Perhaps not surprising, a variety of mathematical approaches have been adopted to quantify synchronization. The most prominent was relative phase and the related metrics of frequency/phase locking, which have a long history of being used to measure interpersonal and intrapersonal coordination.⁵³⁻⁵⁵ A variety of other metrics were used, but the relatively small sample of each metric does not allow for meaningful comparisons between analytical techniques. Convergence on optimal and/or best practices will assist in future cross-study comparisons.

Notably absent from our included studies were clinical populations. As outlined in [table 1](#), all studies in this space thus far have focused on healthy or athletic populations. This could be due to the infancy in this line of research because the roadmap for clinical rehabilitation research often starts with studies on young healthy adults. As such, the synthesis extracted from the 16 studies included in this

Table 2 Summary of the findings of included articles investigating spontaneous interpersonal synchronization in gait

Authors	Setup	Procedure	Findings
Blikslager and de Poel ³⁷	Side-by-side 100-m sprint	Video analysis of the 100-m final of Usain Bolt and Tyson Gay in 12th IAAF World Championship.	No clear evidence for interpersonal synchronization. Both sprinters demonstrated large magnitude variation in step frequency with equally variable differences between runners. Demonstrated variance in step frequency favorable for synchronization.
Chambers et al ³⁸	Pairs walking in city streets	Pose estimation of 2-dimensional YouTube videos when pairs were walking together in a city environment and the extent to which hand-holding affected synchronization.	Tendency for pairs of people to walk in phase or in antiphase with each other.
Harrison and Richardson ³⁹	Walked or jogged a 35-m-long path	Four conditions; alone, visual coupling with 1 partner 0.75 m behind the other and mechanical coupling with a large foam block under vision and vision-occluded states.	Visual and mechanical coupling produced spontaneous interpersonal synchronization. Percentage of phase locking increased from visual (40%), to mechanical (63%), to visuo-mechanical (77%) conditions, respectively. Increased phase locking associated with decreased $SD\Phi$, suggesting increased dynamic stability of the coordination pattern.
Nessler et al ²⁴	Side-by-side treadmill walking	Three conditions: solo, paired without instruction to synchronize with partner, paired with instruction to synchronize in-phase with partner.	Significant increase in stride and lower extremity kinematic variability (SD, maximal Lyapunov exponent) in spontaneous interpersonal synchronization condition compared with remaining conditions.
Nessler and Gilliland ⁴⁰	Side-by-side treadmill walking	Six trials of side-by-side treadmill walking: limited peripheral vision, limited sound, limited peripheral vision and sound, vision and sound normal, vision and sound normal with enhanced tactile input, intentional entrainment.	Total of 62% of pairs exhibited spontaneous frequency locking, and pairs that had higher entrainment also had lower leg length differential. Altering sensory information had little effect on step frequency locking but did have an effect on phase angle locking. Mechanical coupling had the highest phase locking at 46.9%.
Nessler and Gilliland ³³	Side-by-side treadmill walking	Three conditions: solo, paired without instruction to synchronize with partner, paired with instruction to synchronize in-phase with partner.	Intentional synchronization produced smaller, faster steps than independent walking and spontaneous synchronization. No difference between spontaneous synchronization and independent walking conditions.
Nessler et al ⁴¹	Side-by-side treadmill walking	Fourteen different conditions: solo, paired at the same speed, paired with varying treadmill speeds of 1 partner (trials 3-6), paired with varying treadmill slope of 1 partner (trials 7-14).	Pairs with little spontaneous synchronization when both treadmills were the same speed and slope, exhibited tendencies to synchronize when 1 treadmill was manipulated. This effect was conversely demonstrated by pairs that had a tendency to spontaneously synchronize under baseline conditions. Data suggest that spontaneous synchronization of gait is more than matching mechanical properties.

Nessler et al ⁴²	Side-by-side treadmill walking	Three conditions: solo, paired with a research assistant instructed to walk as normally as possible, paired with a research assistant instructed to purposely avoid synchronization with the participant.	A decrease in frequency locking and phase locking between the participants and research assistant observed when the research assistant was told to intentionally desynchronize with the participant relative to the spontaneous synchronization observed when no instructions were given.
Nessler et al ⁴³	Side-by-side treadmill walking	Four trials of treadmill walking: alone, with a partner on side-by-side treadmill, alone with unilateral ankle loading, with a partner, unilateral ankle loading.	Unilateral ankle weighting increased asymmetry of intralimb coordination; however, this effect was reduced during side-by-side walking. Unilateral ankle weight did not affect spontaneous interpersonal coordination; 41% frequency locking for both groups, and 29% phase locking without ankle weighting vs 31% when added ankle loading. Side-by-side walking improved gait asymmetries; however, the effect was the greatest in pairs that consistently synchronized spontaneously.
Sylos-Labini et al ⁴⁴	Side-by-side treadmill walking	Walked at 4 km/h independently and with hand contact both at natural step frequency and with a metronome. Visual and auditory information was obstructed.	Spontaneous interpersonal synchronization was observed 40% of the time in 88% of pairs walking with hand contact. Average amplitude of the contact arm oscillations decreased while electromyograph activity remained the same.
van Ulzen et al ³⁰	Side-by-side treadmill walking	Four trials: baseline walking independently, paired walking without instruction to synchronize, paired walking with instruction to synchronize both in-phase and anti-phase.	Demonstrated episodes of frequency locking in 3 pairs and phase locking in 4 pairs of participants. No difference in stability of in-phase or antiphase coordination and no effect of walking speed or individual preferred stride frequencies.
van Ulzen et al ⁴⁵	Side-by-side treadmill walking	Baseline walking independently, walking independently to an auditory metronome, paired walking to an auditory metronome. Participants instructed to intentionally synchronize to the metronome but not each other. The auditory metronome paced walking to 7 relative phases.	No significant effects of required relative phase on variability were found. Paced walking showed some attraction toward in-phase coordination but not antiphase. The dynamical model for rhythmic interlimb coordination does not readily apply to side-by-side treadmill walking.
Varlet and Richardson ⁴⁶	Side-by-side 100-m sprint	Video analysis of the 100-m final of Usain Bolt and Tyson Gay in 12th IAAF World Championship.	Both runners demonstrated short periods of spontaneous interpersonal synchronization only during the final race in which visual information was available.
Zivotofsky and Hausdorff ⁴⁹	Side-by-side 15-m walk	Four conditions: auditory only, vision only, tactile feedback via hand-holding only, no feedback.	Spontaneous synchrony observed in 50% of walking trials. Strongest in-phase synchrony during tactile feedback condition. Frequent antiphase synchronization in the absence of visual or auditory feedback.

(continued on next page)

Table 2 (continued)

Authors	Setup	Procedure	Findings
Zivotofsky et al ⁴⁸	Side-by-side 70-m walk	Sensory feedback was manipulated through obstructing peripheral vision, blocking auditory feedback, and providing tactile input through hand-holding. Walked under 5 conditions: All 3 manipulations available, hand-holding only, auditory only, visual only, no feedback.	Total of 36% of walks exhibited spontaneous synchrony. Tactile and auditory feedback improved ability to synchronize. Visual feedback was the least effective in synchronizing. Stride time variability increased with increased sensory feedback but not by synchronization.
Zivotofsky et al ⁴⁷	Side-by-side 70-m walk	Three conditions: baseline, simple dual task, complex dual task. Conditions performed both with and without hand-holding.	A simple dual task increased spontaneous synchronization. A complex dual task reduced spontaneous synchronization. Tactile feedback through hand-holding increased synchronization in both attention conditions.

systematic review provides insight for how preclinical research may be formulated. The observation that tactile information led to stronger spontaneous interpersonal synchronization may provide an avenue for study into hand-holding, for example, between a physical therapist and their patient to study the emergence of shared coordination. Nevertheless, more basic science research is needed in this space to better position preclinical research for success. In this context, questions remain regarding the optimal stimulus medium (or combination of mediums), the gait dynamics exhibited by each system that allow for interpersonal coordination to emerge (ie, how different can/should the dynamics of each person be?), the efficacy of synchronizing to a nonbiological partner (ie, a virtual therapist), the frequency/intensity/duration of practice schedules for the shared gait coordination to emerge/stabilize, and the extent to which the new coordination pattern is retained when the partner is removed. Addressing these questions will help develop a framework for this line of research to have clinical application, for which the construct of strong anticipation may serve as a viable candidate.⁵⁶⁻⁵⁹

Study limitations

This systematic review highlighted the common methods, metrics, analytical techniques, and findings in the study of spontaneous interpersonal synchronization in human gait. However, there are several limitations that should be addressed. First, there was an inability to complete a quantitative evaluation (ie, meta-analysis) of the findings because of the wide range of research questions and outcomes used by articles included in this systematic review. Second, the applicability of spontaneous interpersonal synchronization in clinical gait rehabilitation remains a gap in the literature because none of the included studies applied this technique to clinical populations. Third, a relatively small number of articles (n=16) met the inclusion criteria for this systematic review topic, highlighting the limited scope of research in this area. The fourth limitation refers to sample sizes in the included studies. Excluding the observational study³⁸ that included N=348, the average sample size of the remaining 15 articles was 22.9 participants (median, 22 participants). While samples of this size are not uncommon for motor learning studies, the issue of small sample sizes and generalized applicability in motor learning research has been discussed.⁶⁰ Lastly, nearly half (n=7) of the 16 studies included in this systematic review are 10 or more years old.

Conclusions

The articles included in this systematic review showed that spontaneous synchronization in the gait of 2 humans can occur and the strength of the synchronization is modulated by the nature of the task and the sensory information available. Collectively, the data suggest that side-by-side walking may be an effective intervention to improve gait in a rehabilitation setting. Walking alongside an intact locomotor system may provide a more effective and biologically variable attractor signal for rehabilitation of gait behavior aligned with a

Table 3 Summary of movement data measures for spontaneous interpersonal synchronization

Authors	Data Origin	Measurement	Analysis
Blikslager and de Poel ³⁷	TV video footage	Between-leg spatial angles	Discrete relative phase, continuous relative phase, step frequency
Chambers et al ³⁸	YouTube videos	Ankle displacement	Relative phase (mean) and walking frequency
Harrison and Richardson ³⁹	Electrogoniometry	Knee flexion/extension	Relative phase (mean \pm SD), percentage phase locking
Nessler et al ²⁴	Motion capture	Lower extremity kinematics	Step frequency, frequency locking, recurrence plot, Lyapunov exponent, knee angle, ankle angle, step length, step height, frontal plane ankle movement, knee vertical trajectory
Nessler and Gilliland ⁴⁰	Motion capture	Ankle displacement	Step frequency, percent frequency locking, mean frequency difference, relative phase
Nessler and Gilliland ³³	Motion capture	Lower extremity kinematics	Mean step length, step height, step time, and step time SD; peak swing velocity, ankle plantarflexion, and hip flexion; ankle, knee, and hip angle excursion; step frequency, percentage frequency locking
Nessler et al ⁴¹	Motion capture	Ankle displacement	Step frequency, percentage frequency locking, stride length, stride time
Nessler et al ⁴²	Motion capture	Lower extremity kinematics	Relative phase, percentage frequency locking, percentage phase locking, knee angle, ankle angle, stride length, stride time, stride height, peak swing velocity of each step, detrended fluctuation analysis, approximate entropy, Lyapunov exponent
Nessler et al ⁴³	Motion capture	Heel and toe displacement	Step frequency, percent frequency locking, percent phase locking, relative phase (SD), cross spectral coherence, gait asymmetry, phase coordination index, stride length, stride height, stride duration
Sylos-Labini et al ⁴⁴	Motion capture, EMG, force/torque sensors	Full body kinematics, EMG of upper limb muscles, interaction forces	Kinematics: stride frequency, relative phase, frequency locking, phase difference (ie, locking); EMG: center of activity, silhouette value; Interaction forces: amplitude, orientation, spherical contour of the density distribution of the 3-dimensional force vector
van Ulzen et al ³⁰	Motion capture	Lower extremity kinematics	Stride frequency, relative phase (mean \pm SD), frequency locking, phase locking
van Ulzen et al ⁴⁵	Motion capture	Lower extremity kinematics	Stride frequency, relative phase (mean \pm SD); During metronome walking: mean error and absolute mean effort between observed and required relative phase (ie, phase shift and absolute phase shift)
Varlet and Richardson ⁴⁶	TV video footage	Step timing	Relative phase (distribution), phase locking
Zivotofsky and Hausdorff ⁴⁹	Video	Level of synchronization	Synchrony score -3 to 3 .
Zivotofsky et al ⁴⁸	Trunk-mounted triaxial accelerometer	Trunk vertical acceleration	Mean stride time, asymmetry of cadence, relative phase, phase difference (ie, locking), gait synchronization index (ie, entropy of phase difference), phase shift, cadence asymmetry, coefficient of variation of stride time
Zivotofsky et al ⁴⁷	Trunk-mounted triaxial accelerometer	Trunk vertical acceleration	Mean stride time, asymmetry of cadence, relative phase, phase difference (ie, locking), gait synchronization index (ie, entropy of phase difference), phase shift, cadence asymmetry, coefficient of variation of stride time

Abbreviation: EMG, electromyograph.

suggestion to apply dynamical systems theory to improve locomotor performance.⁶¹ Moreover, spontaneous synchronization may be beneficial in that it might require less corrective movements to maintain synchrony relative to intentional synchronization conditions.³² Further research needs to be done to fully understand the influence of spontaneous interpersonal synchronization on the variability of gait behavior and implications for use as a rehabilitation tool.

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